Annotated Bibliography

Uncertainty Analysis and its Application to Hydraulic Measurements and Experimentation

Standards for Determining and Expressing Uncertainty

AIAA, 1999. Assessment of Experimental Uncertainty with Application to Wind Tunnel Testing, Standard S-071A-1999. American Institute of Aeronautics and Astronautics. 84 pp. **{Wahl}**

The 1995 version of this standard has been proposed by Muste for adoption by the hydraulic engineering community. This is the latest version.

ASME (1998). Test Uncertainty: Instruments and Apparatus. ASME PTC 19.1-1998. **{Gonzalez}**

The scope of this supplement is to specify procedures for evaluation of uncertainties in individual test measurements, arising from both random errors and systematic errors, and for the propagation of random and systematic uncertainties into the uncertainty of a test result. The various statistical terms involved are defined in the Nomenclature (para. 3.1) and Glossary (para. 3.2). The end result of a measurement uncertainty analysis is to provide numerical estimates of systematic uncertainties, random uncertainties, and the combination of these into a total uncertainty with an approximate confidence level.

BSR/ASME PTC 19.1-2003, Test Uncertainty (revision of ANSI/ASME PTC 19.1-1998).

Description from ANSI Standards Action VOL. 34, #7 Feb. 14, 2003 - *The scope of this Supplement is to specify procedures for evaluation of uncertainties in test parameters & methods, and for propagation of those uncertainties into the uncertainty of a test result.*

ASME (1983). Measurement Uncertainty for Fluid Flow in Closed Conduits. ASME MFC-2M-1983 (R1988).

Description from ASME Publication Catalog - *This Standard presents a working outline detailing and illustrating the techniques for estimating measurement uncertainty for fluid flow in closed conduits. The statistical techniques and analytical concepts applied herein are applicable in most measurement processes. Section 2 provides examples of the mathematical model applied to the measurement of fluid flow. Each example inches a discussion of the elemental errors and examples of the statistical techniques. An effort has been made to use simple prose with a minimum of jargon. The notation and definitions are given in Appendix A and are consistent with ISO 3534, Statistic-Vocabulary and Symbols (1977).*

MFC.5M - 1985 Measurement of Liquid Flow in Closed Conduits Using Transit-Time Ultrasonic Flowmeters.

Description from ASME Publication Catalog – This Standard applies only to ultrasonic flow meters that base their operation on the measurement of transit times of acoustic signals. Further, this Standard concerns only the application of such meters when used to measure the volumetric flow rate of a liquid exhibiting homogeneous acoustic properties and flowing in a completely filled closed conduit. Not covered by this Standard are ultrasonic flow meters that derive volumetric flow rate from measurements of the deviation, scattering (Doppler flow meter), or correlation of acoustic signals. This Standard provides: (a) a description of the operating principles employed by the ultrasonic flow meters covered in this Standard; (b) a description of *error sources and performance verification procedures; (c) a common set of terminology, symbols, definitions, and specifications.*

ISO Guide to the Expression of Uncertainty in Measurement, first edition, 1993, corrected and reprinted 1995. **{Gonzalez}**

The Guide is sponsored by seven international organizations and published in their name by ISO. Namely, , Bureau International des Poids et Mesures (BIPM), International Electrotechnical Commission (IEC), International Federation of Clinical Chemistry (IFCC), International Organization for Standardization (ISO), International Union of Pure and Applied Chemistry (IUPAC), International Union of Pure and Applied Physics (IUPAP), International Organization of Legal Metrology (OIML). The Guide is available in U.S. ($25) and international ($92) editions. The editions contain the same material, differing only in decimal marker, spelling, and size. The ISO International Vocabulary of Basic and General Terms in Metrology (VIM), 1993, a companion document to the GUM, is available only in an international edition ($71). The U.S. edition of the GUM is entitled: American National Standard for Expressing Uncertainty--U.S. Guide to the Expression of Uncertainty in Measurement, ANSI/NCSL Z540-2-1997

Cox, M. G., and Harris, P. M. "GUM Supplements", CIE Expert Symposium on Uncertainty Evaluation, Method for Analysis of Uncertainties in Optical Radiation Measurement, Vienna, Austria. **{Gonzalez}**

<u>Authors Abstract:</u> *This paper is concerned with the reliable evaluation of uncertainties within metrology, using approaches that are as objective as economically possible. It is motivated by two principal considerations. One is that the primary guide on uncertainty evaluation, the Guide to the Expression of Uncertainty in Measurement (GUM), published by ISO, indicates that although it can be expected to be very widely applicable the approach it predominantly endorses contains some limitations. The other is that on the basis of the authors' considerable contact with practitioners in the metrology community it is evident that important classes of problem are encountered that are indeed subject to these limitations.*

ISO 6416 (1992).

Measurement of liquid flow in open channels—Measurement of discharge by the ultrasonic (acoustic) method.

Uncertainty Analysis – General Information

Abernethy, A.B., Benedict, R.P., and Dowdell, R.B., 1985. ASME measurement uncertainty. Journal of Fluids Engineering, Transactions of the ASME, June 1985. **{Wahl PDF and Wahlin}**

Available on the web at http://www.barringer1.com/drbob-bio_files/ASME83.pdf

This paper gives history, background, and discussion of committee activities leading to the development of the new (in 1985) ASME measurement uncertainty methodology, which is the basis for two ASME/ANSI standards (ASME PTC 19.1 Measurement Uncertainty among them).

Abernethy, R., and Ringhiser, B. (1985). "The History and Statistical Development of the New ASME-SAE-AIAA-ISO Measurement Uncertainty Methodology." 20th AIAA/SAE/ASME Joint Propulsion Conference. **{Gonzalez}**

This is a seminal paper that highlights not only the issues on the methodologies adopted across disciplines for measurement uncertainty, but also discusses the need to establish standard methodologies for (a) curve fitting; (b) weighting competitive answers; and (c) outlier detection.

Ang H-S. A., Tang, W.H. Tang (1990). Probability Concepts in Engineering Planning and Design. John Wiley, NY. Vol. II. **{Gonzalez}**

A very good reference on the subject of Probability and Statistics applied to civil engineering. Of particular interest is Chapter 6, which covers reliability and uncertainty analysis. The subject is presented from a rigorous mathematical standpoint, and the methods presented are relevant to uncertainty analysis of indirect flow measurements based on uncalibrated simplified rating algorithms.

ASME. (1991).

- September 1991 Editorial on Experimental Uncertainty. **{Wahl PDF}**
- Journal of Fluids Engineering Policy on Reporting Uncertainties in Experimental Measurements and Results. **{Wahl PDF}**
- Journal of Fluids Engineering Editorial Policy Statement on the Control of Numerical Accuracy. **{Wahl PDF}**

Guidelines for presenting uncertainty analysis results for papers submitted to the Journal of Fluids Engineering. JFE has had some requirement for uncertainty analysis in submitted papers since 1975.

ASME. (????). "Policy on reporting uncertainties in experimental measurements and results." *J. Heat Transfer*. **{Wahlin, PDF}**

Guidelines for presenting uncertainty analysis results for papers submitted to the Journal of Heat Transfer.

Baker, C.R., (2000). Flow Measurement Handbook, Cambridge University Press, Cambridge, U.K. **{Gonzalez}**

The book covers important aspects of the physics of fluid flow and includes an appendix on the statistics of flow measurements. The handbook ponders the laboratory ideal and the realities of field experience. It apparently provides good practical advice on the design, operation, and performance of a broad range of flow meters for pipe flow. Measuring devises are often followed by a description of the theory behind their principle of operation. A description of the book as well as a sample chapter can be found at http://books.cambridge.org/0521480108.htm

---

Belter, D.L. "Application of uncertainty methodology at the Boeing Aerodynamics Laboratory." 19th AIAA Advanced Measurement and Ground Testing Technology Conference, New Orleans, LA, June 17-20, 1-6, AIAA Paper 96-2215. {**Wahlin, PDF}**

This paper is a brief overview of how the Boeing Aerodynamics Laboratory is applying the following standards: 1) Advisory Group for Aerospace Research and Development AGARD-AR-304 "Quality assessment for wind tunnel testing" and 2) American Institute of Aeronautics and Astronautics AIAA S-071-1995 "Assessment of wind tunnel data uncertainty."

Brown, K.K., and Coleman H.W. (1996). *Determination of uncertainties for the new SSME model.* NASA contract number NAS8-38609 D.O. 140. Propulsion Research Center, University of Alabama, Huntsville, AL. **{Wahlin}**

This work presents uncertainty information for measurements (temperature, pressure, rotation speed, valve positions, etc.). It has a good overview of uncertainty analysis and a good section on how to assess the uncertainty in linear regression. SSME stands for Space Shuttle Main Engine. Delivery Order (D.O.) 106 dealt with experimental uncertainty in venturi meter flow rates (this is summarized in Brown et al. (1998)).

Brown, K.K., Coleman, H.W., Steele, W.G., and Taylor, R.P. (1996). "Evaluation of correlated bias approximations in experimental uncertainty analysis." *AIAA Journal*, 34(5), 1013-1018. **{Wahlin}**

The authors present a method for approximating the effect of correlated bias errors in experimental uncertainty analysis. This is a very interesting paper.

Brown, K.K., Coleman, H.W., and Steele, W.G. (1998). "A methodology for determining experimental uncertainties in regressions." *J. of Fluids Engineering*, 120, 445-456. **{Wahlin}**

The authors apply uncertainty propagation techniques to the linear regression analysis equations. They demonstrate their methodology on the calibration of a venturi meter. This is a good paper.

Cameron, J.M., 1974. *The Use of the Method of Least Squares in Calibration,* National Bureau of Standards, Report NBSIR 74-587. **{Wahl PDF}**

Available on the web at http://patapsco.nist.gov/mel/div821/Publications/NBSIR 74-587.pdf

Very mathematical discussion of the use of least squares regression.

Castrup, H. (2000). "Estimating bias uncertainty." Integrated Sciences Group, Bakersfield, CA. **{Wahlin}**

Technical paper discussing methods for estimating bias of reference parameters. Has a section that talks about drift.

Coleman, H.W., and Steele, W.G. (1995). "Engineering application of experimental uncertainty analysis." *AIAA Journal*, 33(10), 1888-1896. **{Wahlin}**

*The authors present the assumptions and approximations of ISO's **Guide to the expression of uncertainty in measurement** (1993). They also compare this method with previously published uncertainty analysis approaches.*

Coleman, H.W., and Steele, W.G. 1999. *Experimentation and Uncertainty Analysis for Engineers*, 2nd Ed., John Wiley & Sons, New York, 275 pp. **{Wahl}**

The authors of this text have been two of the leading developers of modern uncertainty analysis techniques and have been involved in the preparation of many of today's most commonly referenced guides on the topic. The book addresses basic concepts and statistics as well as applications to experimental planning, design, debugging, execution, data analysis, and reporting. Appendices provide theoretical background and a comparison of alternative and previously used uncertainty analysis methods. This is an excellent resource.

DeLaurentis, D.A., and Mavris, D.N. (2000). "Uncertainty modeling and management in multidisciplinary analysis and synthesis." American Institute of Aeronautics and Astronautics. **{Wahlin PDF}**

This paper outlines a formal approach for modeling uncertainty in multidisciplinary design problems. A new method for propagating the uncertainty to find robust design solutions is developed and described.

Doiron, T., and Stoup, J., (1997). Uncertainty and Dimensional Calibrations. *Journal of Research of the National Institute of Standards and Technology,* Vol. 102, No. 6. 30 pp. **{Wahl PDF}**

Available on the web at http://patapsco.nist.gov/mel/div821/Publications/NIST J Res Nov-Dec 97 102-6.pdf

Describes implementation by NIST of measurement uncertainty standards for dimensional calibrations of several types of gages, including sieves.

Eisenhart, C., Ku, H.H., and Colle, R. (1983). *Expression of the uncertainties of final measurement results: Reprints.* National Bureau of Standards, Washington DC. **{Wahlin}**

These papers stress the need to clearly state the uncertainties of reported values. It has a nice qualitative discussion of uncertainty and some tables with the "appropriate" format for reporting uncertainty estimates of various measurements and values.

Ellison, S.L.R., Rosslein, M., and Williams, A., eds. (2000). *Quantifying uncertainty in analytical measurement*. EURACHEM/CITAC Guide CG 4. Available on the web at http://www.measurementuncertainty.org/mu/quam2.pdf **{Wahl and Wahlin PDF}**

Despite the general-sounding title, this guide is specific to quantitative chemical analysis. It is of interest primarily to see how another field has developed a guide for application of the ISO-GUM. Contains lots of examples.

EURACHEM. (1999). *Quantifying uncertainty in analytical measurement.* EURACHEM Workshop, Helsinki. **{Wahlin}**

Extensive overview of all aspects of uncertainty analysis. It includes lots of examples as well as appendices with general statistical information. It follows ISO's ***Guide to the expression of uncertainty in measurement.***

European Co-operation for Accreditation. (1999). *Expression of the uncertainty of measurement in calibration*. Publication Reference EA-4/02. **{Wahlin PDF}**

This publication presents a methodology for expressing uncertainty for accredited calibration laboratories. It is very similar to ISO's ***Guide to the expression of uncertainty in measurement****. There are many examples at the end of this publication.*

Holman, J.P. (1989). *Experimental methods for engineers.* Fifth edition, McGraw-Hill, New York, NY. **{Wahlin}**

Contains some basic uncertainty analysis stuff. Mostly concentrates on measurement techniques for various parameters (e.g., temperature, pressure, and flow).

Hudson, S.T., Bordelon, W.J., and Coleman, H.W. (1996). "Effect of correlated precision errors on uncertainty of a subsonic Venturi calibration." *AIAA Journal*, 34(9), 1862-1867. **{Wahlin}**

This paper demonstrates that correlated precision errors are not always negligible and that they can have a significant influence on the results of an uncertainty analysis.

Intergovernmental Panel on Climate Change. (????). *Conceptual basis for uncertainty analysis*. IPCC good practice guidance and uncertainty in national greenhouse gas inventories, annex 1. **{Wahlin PDF}**

Qualitative assessment of uncertainty for greenhouse gas inventories. Relies heavily on ISO standards.

Kline, S.J., and McClintock, F.A. (1953). "Describing uncertainties in single-sample experiments." *Mechanical Engineering*, 75, 3-7. **{Wahlin}**

This is one of the first papers on uncertainty analysis. Apparently, this is the first paper to present the root-mean-sum equations for uncertainty.

Kline, S.J., 1985. The purposes of uncertainty analysis. *Journal of Fluids Engineering,* Transactions of the ASME, June 1985. **{Wahl and Wahlin}**

This was the introductory paper in a special issue of JFE that presented several papers from a 1983 symposium on uncertainty analysis. The paper touches such topics as the concepts of uncertainty in experiments, the uses of uncertainty analysis, and whether or not uncertainty analyses are worthwhile. The second appendix to the paper presents several persuasive case histories that illustrate the potential value of uncertainty analysis.

Kline, S.J., 1985. Closure to 1983 Symposium on Uncertainty Analysis. Journal of Fluids Engineering, Transactions of the ASME, June 1985. **{Wahl and Wahlin}**

This is an excellent summary of the outcomes of the 1983 symposium on uncertainty analysis. Kline emphasizes two important conclusions:

1. Uncertainty analysis is an essential ingredient in planning, controlling, and reporting experiments. *The important thing is that a reasonable uncertainty analysis be done.* **ALL DIFFERENCES OF OPINION ABOUT APPROPRIATE METHODS ARE SUBSIDIARY TO THIS CONCLUSION.** (my emphasis)
2. It is particularly important to use an uncertainty analysis in the planning and check out stages of an experiment!

Ku, H.H. 1988. *Statistical Concepts in Metrology — With a Postscript on Statistical Graphics,* National Bureau of Standards Special Publication 747. **{Wahl PDF}**

Available on the web at http://patapsco.nist.gov/mel/div821/Publications/NBS Special Publication 747.pdf

A detailed review of statistical concepts that relate to uncertainty analysis. The postscript on statistical graphics is a good source of ideas for how to examine experimental results graphically during the debugging phase of an experiment.

Lassahn, G.D., 1985. Uncertainty definition. Journal of Fluids Engineering, Transactions of the ASME, June 1985. **{Wahl and Wahlin}**

From the 1983 symposium on uncertainty analysis. This short, thought-provoking paper addresses philosophical questions related to barriers to our understanding and use of uncertainty analysis concepts and procedures.

Mandel, J. (1984). *The Statistical Analysis of Experimental Data*, Dover Publications, Inc., Mineola, N.Y. **{Gonzalez}**

This book covers various issues regarding experimental data analysis. The chapter in the mathematical framework of statistics part II is particularly useful for understanding the general problem of derived measurements as well as the law of propagation of errors for functions of several random variables.

Mandel, J., and Nanni, L. (1986). *Measurement evaluation*. National Bureau of Standards Special Publication 700-2, Industrial Measurement Series. **{Wahl PDF}**

Available on the web at http://patapsco.nist.gov/mel/div821/Publications/NBS Special

Publication 700-2.pdf

This work is a good overview of basic statistical concepts and control charts. This work was developed for health-related fields of research and is a good presentation of familiar topics from a different perspective.

Mays, L.W., and Tung, Y.K. (1992). *Hydrosystems engineering and management*. McGraw-Hill, New York, NY. **{Wahlin}**

Some basic uncertainty analysis. Concentrates mostly on reliability issues.

Moffat, R.J. (1982). "Contributions to the theory of single-sample uncertainty analysis." *Journal of Fluids Engineering,* Vol. 104, 250-260. **{Wahl and Wahlin}**

Moffat presents three levels of uncertainty analysis which he calls zeroth, first, and Nth order. In zeroth order analysis the experiment is assumed rock-steady in time, so that the only errors are due to interpolation uncertainty (i.e., errors in reading experimental displays). This is used mainly for preliminary planning. A first order analysis includes process unsteadiness effects and interpolation effects, but instrument properties (i.e., their uncertainty characteristics) are assumed fixed in time. This is useful during the developmental stage of an experiment. The Nth order analysis includes uncertainties due to interpolation, unsteadiness, and instrument calibration variations during the experiment. It is used for reporting the final results. This paper was developed in connection with heat transfer and fluid mechanics research experiments. The concepts introduced here have been incorporated into modern uncertainty analysis methodology. The discussions of this paper by Dowdell and Abernethy are also very interesting (published in same volume).

Moffat, R.J. (1985). "Using uncertainty analysis in the planning of an experiment." *Journal of Fluids Engineering*, Vol. 107, 173-178. **{Wahlin}**

Moffat outlines a procedure for using uncertainty analysis in the planning of experiments. This paper is from the 1983 symposium on uncertainty analysis.

Moffat, R.J. (1988). "Describing the uncertainties in experimental results." *Experimental Thermal and Fluid Science*, 1, 3-17. **{Wahlin}**

This paper presents a general description of the sources of errors in engineering measurements and the relationship between error and uncertainty. The basic mathematics of both single-sample and multiple-sample analysis are also presented. Geared for heat transfer and fluid mechanics.

National Engineering Laboratory. (2002). *Flowmetering current practice and uncertainty case studies*. A report for NMSD Department of Trade and Industry, London, UK. **{Wahlin PDF}**

A British publication that discusses the issues which can affect the quality of flow data and considers data analysis techniques which can be used to indicate flow meter performance. This publication has some good examples.

Nielsen, H.S. 1997. Using the ISO Guide to the Expression of Uncertainty in Measurements to determine calibration requirements. National Conference of Standards Laboratories Workshop & Symposium. http://www.hn-metrology.com/isogum.htm **{Wahl}**

More information on how the measurement standards industry is applying the ISO standards for expressing uncertainty.

Phillips, S.D., and Eberhardt, K.R. (1997). "Guidelines for expressing the uncertainty of measurement results containing uncorrected bias." *J. of Research of the National Institute of Standards and Technology*, 102, 577-585. **{Wahlin}**

Extends ISO's ***Guide to the Expression of Uncertainty in Measurement*** *by accounting for uncorrected systematic errors.*

Taylor, B.N., and Kuyatt, C.E. 1994. Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurement Results. National Institute of Standards and Technology Technical Note 1297. **{Wahl PDF}**

Available on web at http://physics.nist.gov/Document/tn1297.pdf and http://physics.nist.gov/Pubs/guidelines/contents.html

An example of the metrology industry's guidelines for applying the ISO standards. Very comprehensive, with lots of definitions, appendices, and references.

Taylor, J.R. (1997). *An introduction to error analysis: the study of uncertainties in physical measurements.* University Science Books, Sausalito, CA. **{Wahlin}**

Very good introduction to uncertainty analysis. It is written in plain English and is very easy to understand. The 1982 edition of this text was recommended by S.J. Kline in his closure to the 1983 ASME Symposium on Uncertainty Analysis.

Tripp, J.S., and Tcheng, P. (1999). *Uncertainty analysis of instrument calibration and application.* NASA Technical Paper 1999-209545. **{Wahlin}**

Uses confidence and prediction intervals to determine the uncertainty in the calibration procedure.

Tung, Y.K. (1999). "Risk/reliability-based hydraulic engineering design." *Hydraulic design handbook*. Ed. Mays, L. McGraw-Hill, New York, NY. **{Wahlin}**

Tung gives an overview of uncertainty analysis, including some techniques that I have never heard of such as Mellin Transformation and Rosenblueth's Probabilistic Point Estimation Method. Most of the chapter concentrates on reliability analysis.

USACE. (1996). *Risk-based analysis for flood damage reduction studies.* USACE Engineering Manual 1110-2-1619. **{Wahlin PDF}**

This manual has chapters on the uncertainty of discharge-probability functions, stage-discharge functions, and stage-damage functions.

Yen, B.C., and Tung, Y.K. (1993). *Reliability and uncertainty analysis in hydraulic design*. ASCE, New York, NY. **{Wahlin and Gonzalez}**

This monograph is a collection of papers on reliability and uncertainty analysis, pertinent to the design and safety of hydraulic structures. It covers everything from new advances in uncertainty analysis to dam safety to coastal floods. There is one article by Tung and Yen about new advances in uncertainty analysis. The committee is unfamiliar with some of these new methods. The first four papers discuss various techniques pertinent to reliability and uncertainty analyses. The next nine papers explore how these techniques can be applied to dam safety, coastal floods, and hydraulic structures. The report ends with a reprint of an article by Vrijling on the Eastern Scheldt Storm Surge Barrier of the Delta Project in the Netherlands and the use of reliability analysis for sewer design. The topics of uncertainty of hydraulic and hydrologic monitoring, as well as experimental

uncertainty and measurement error are not specifically addressed.

Web Resources on Uncertainty Analysis

http://physics.nist.gov/cuu/ – The NIST Reference on Constants, Units and Uncertainty.

http://physics.nist.gov/cuu/Uncertainty – Uncertainty of Measurement Results: Essentials of Expressing Measurement Uncertainty. Introduction to the essentials of the approach to expressing measurement uncertainty. A web site provided as a public service by the National Institute of Standards and Technology (NIST).

http://www.gum.dk – A web site dedicated to information on the ISO-GUM. Includes English and Danish pages, and commercial software (GUM Workbench) for performing uncertainty analysis.

http://www.measurementuncertainty.org/ – A European source of information about uncertainty analysis. Apparently sponsored by an organization called Eurachem. This site provides a guidance document for analytical chemistry applications (the EURACHEM/CITAC Guide), example applications, a glossary, and a relatively active discussion forum. ***At this time, this site only works with Internet Explorer.***

http://patapsco.nist.gov/mel/div821/Publications/Publications.asp – Engineering Metrology Toolbox: Selected Publications. Provides links to several NIST publications related to uncertainty.

http://members.asme.org/Catalog/index.cfm – This site has a list of publications on ASME Codes and Standards. Of particular interest to flow measurement errors and uncertainty are the publications listed under the flow measurement category. However, most of these publications are applicable to pipe flow.

http://web.usna.navy.mil/~ratcliff/EM375/Errors/Errors.pdf – *Uncertainty in measurements and the propagation of errors.* Apparently a set of course notes.

http://mathworld.wolfram.com – Eric Weisstein's world of Mathematics. A free service for the mathematical community provided by Wolfram Research, makers of *Mathematica*, with additional support from the National Science Foundation. The link to the Error Propagation page in this site is http://mathworld.wolfram.com/ErrorPropagation.html.

http://www.asp.ucar.edu/colloquium/1992/notes/part1/node6.html – This site contains a primer on measurement uncertainty in the form of hypertext.

- 2.1 General comments
- 2.2 Classification of error sources
- 2.3 More terminology
- 2.4 The ASME measurement-uncertainty formulation
- 2.5 Propagation of uncertainty estimates
- 2.6 Monte Carlo techniques

Applying Uncertainty Analysis to Hydraulic Engineering

Muste, M., and Stern, F. (2000). "Proposed uncertainty assessment methodology for hydraulic and water resources engineering." *Joint ASCE Conference on Water Resources Engineering and Water Resources Planning and Management*, Minneapolis, MN, July 30 – August 2. **{Wahl and Wahlin}**

This conference paper advocates the use of AIAA standard S-071-1995 as the standard that ASCE adopts for uncertainty analysis. It also gives a brief overview of S-071-1995. There is an updated version of this standard (S-071A-1999).

A set of standards used in mechanical and aeronautical engineering for estimating measurement uncertainty are evaluated and compared in the light of basic statistical principles. A recommendation is made to adopt the First Order Variance (FOV) method for estimating total uncertainty as suggested by AIAA.

Ogden, F.L. (1996). "Experimental uncertainty and measurement errors in hydraulic engineering." *Proc. ASCE North American Water and Environment Congress*, Anaheim, CA. **{Wahl and Wahlin PDF}**

This paper outlines the objectives of a previous formulation of this task committee.

Stern, F., Muste, M., Beninati, M.L., and Eichinger W.E. (1999). "Summary of experimental uncertainty assessment methodology with example." *IIHR Technical Report No. 406*, University of Iowa, Iowa City, IA. **{Wahlin PDF}**

This report proposes using AIAA standard S-071-1995 for uncertainty analysis. They also use a lot of stuff from Coleman and Steele. The example they present is on the uncertainty of the measurement of density and kinematic viscosity. There is an updated version of this standard (S-071A-1999).

Hydraulic Parameters - Miscellaneous

Blanton, J.N., 1995, "Uncertainty Estimates of Test Section Pressure and Velocity in the Large Cavitation Channel," *Joint Propulsion Conference of the AIAA/ASME Ground Test Technical Committee*, AIAA 95-3079. **{Gonzalez}**

This paper appears to describe the velocity and pressure measurement capabilities of the Morgan Large Cavitation Channel (LCC) in Memphis Tennessee. And provides an uncertainty analysis of velocity and pressure measurements for the facility.

Cesare, M.A. (1991). "First-order analysis of open-channel flow." *Journal of Hydraulic Engineering,* ASCE, 117(2), 242-247. **{Wahlin}**

This paper uses first-order reliability methods to incorporate uncertainties involved in open-channel hydraulics and compares the results to the traditional method.

Gluhovsky A., and Politis, D. N., Subsampling-based Inference for the Parameters of the Atmospheric Boundary Layer. Interface 2002 Conference, Montreal Canada. Interface Foundation of North America

Employing of computer-intensive subsampling methodology can considerably improve the statistical validity of atmospheric data analysis. This paper exemplifies how this methodology makes possible to do statistically significant comparisons between statistical characteristics of the atmospheric boundary layer computed from observational and large-eddy simulation data *sets. Issues regarding the estimation of the statistical characteristics of data sets by temporal and spatial averaging are discussed.*

Johnson, P.A. (1996). "Uncertainty of hydraulic parameters." *Journal of Hydraulic Engineering*, ASCE, 122(2), 112-114. **{Wahlin}**

This paper presents a summary of uncertainty work that has been done in the past. Parameters examined include: Manning's n, channel slope, particle size, friction slope, sediment specific weight, and flow velocity.

Lee, H.L., and Mays, L.W. (1986). "Hydraulic uncertainties in flood levee capacity." *Journal of Hydraulic Engineering*, ASCE, 112(10), 928-934. **{Wahlin}**

The hydraulic uncertainty is evaluated through a first-order analysis of uncertainties of Manning's equation. This study shows that the roughness coefficient and the friction slope dominate the variation in hydraulic uncertainty in that they account for 95% of the hydraulic uncertainty.

Lenschow, D.H., J. Mann and L. Kristensen, 1994: How long is long enough when measuring fluxes and other turbulence statistics? J. Atmos. and Oceanic Tech. , 11, 661-673. **{Gonzalez}**

This paper seems to address the very important issue of the record length in measuring turbulent flows.

Park, J.T., Cutbirth, J.M., and Brewer, H.W. (2003). " Hydrodynamic Performance of the Large Cavitation Channel (LCC)," *Proc. of 4th ASME/JSME Joint Fluids Engineering Conference*, Honolulu, Hawaii. **{Gonzalez}**

This paper outlines the hydrodynamic performance of the Morgan Large Cavitation Channel (LCC) in Memphis, Tennessee. The LCC is the world's largest water tunnel. Results are reported in the paper on three key characteristics of the tunnel: temporal stability, spatial uniformity, and turbulence. It provides a very good example of how flow measurement uncertainty can be computed for laser Doppler anemometry, hot-film and constant temperature anemometry.

Soulsby, R. L. (1980). "Selecting Record Length and Digitization Rate for Near-Bed Turbulence Measurements," *J. Phys. Oceanography*, 10, 208-218. **{Gonzalez}**

This paper addresses the important issues of the effect of sampling times and spatial resolution on the accuracy of measurements of mean velocity and turbulence quantities in a turbulent boundary layer.

Sreenivasen, K.R., Chambers, A.J., and Antonia, R.A. (1978) "Accuracy of moments of velocity and scalar fluctuations in the atmospheric surface layer." *Boundary-Layer Meteorology*, **14**, 341-359, 1978

This paper seems to address the issue of the effect of sampling on the accuracy of measurements of mean velocity and turbulence quantities in atmospheric boundary layer.

Tung, Y.K. (1990). "Mellin transform applied to uncertainty analysis in hydrology/hydraulics." *Journal of Hydraulic Engineering*, ASCE, 116(5), 659-674. **{Wahlin}**

The author introduces a mathematical technique called the Mellin transform. He gives two examples to demonstrate the application of the Mellin transform to uncertainty analysis of hydrologic and hydraulic problems.

Yeh, K.C., and Tung, Y.K. (1993). “Uncertainty and sensitivity analysis of pit-migration model.” *Journal of Hydraulic Engineering*, ASCE, 119(2), 262-283. **{Wahlin}**

This paper analyzes the uncertainties of a pit migration model using three methods including the first-order variance estimation method, the point estimation technique, and Latin hypercubic sampling.

Discharge Measurement – General Information

Abernethy, A.B., 1985. Fluid Flow Measurement Uncertainty. ISO/DIS 5168, 10th draft. 54 pp. **{Wahl PDF. I have assembled the 4 PDF files at this site into a single file.}**

Available on the web at http://www.barringer1.com/drbob-bio.htm.

According to a handwritten note from Abernethy included in the PDF file, this standard was approved by unanimous Committee vote in 1987, and by world vote in 1988, (17 for, France and Italy against), but was never published because the French delegation controlled the ISO TC30 Secretariat. Dr. Abernethy believes this earlier 10th draft was better than the 12th draft, which was the one approved by vote. It was apparently later published, as a 1998 version is for sale from ISO. Abernethy says this was the best standard he ever wrote.

I have also seen references in some papers to a 2001 version. We do not have the official ISO publication.

ISO/TR 7066-1:1997 Assessment of uncertainty in calibration and use of flow measurement devices -- Part 1: Linear calibration relationships

We do not have this publication

ISO 7066-2:1988. Assessment of uncertainty in the calibration and use of flow measurement devices -- Part 2: Non-linear calibration relationships

We do not have this publication

Streamflow – Indirect Estimation Methods

Hardison, C.H., and Moss, M.E. (1972). “Accuracy of low-flow characteristics estimated by correlation of base-flow measurements.” *Manual of hydrology: Part 2. Low-flow techniques*, USGS Water-Supply Paper 1542-B. **{Wahlin}**

The authors present equations and graphs to evaluate the accuracy of low flow measurements at ungaged sites. The method is based on the regression equation and the length of record used. There is an appendix at the end where E.J. Gilroy outlines the derivations of the equations.

Moss, M.E. (1972). *Serial-correlation structure of discretized streamflows.* USGS Open-File Report 72-262, Fort Collins, CO. **{Wahlin}**

Moss presents a model to estimate the serial-correlation structure of discretized streamflows on a monthly and annual basis. The model accounts only for that component of the correlation that is caused by baseflow. Direct runoff is treated as random noise. ***Not particularly useful.***

Murdock, R.U., and Gulliver, J.S. (1993). "Prediction of river discharge at ungaged sites with analysis of uncertainty." *J. Water Resources, Planning, and Management*, 119(4), 473-487. **{Wahlin}**

The authors outline a technique for assigning uncertainty to the estimation of the cumulative probability distribution functions (flow-duration curves) for river discharge at ungaged sites. ***Not particularly useful.***

Current-Meter Discharge Measurements

Carter, R.W., and Anderson, I.E. (1963). "Accuracy of Current Meter Measurements," *J. Hydr. Engrg*., ASCE, 89(4), 105-115. **{Gonzalez}**

This paper addresses the uncertainty of current-meter measurements based on field data collected in well-behaved flow environments. Total uncertainty is computed as the Root Sum Square (RSS) of the uncertainty due to sampling time, velocity profile, and number of subsections. The reported total uncertainty seems inconsistent with the work referred to in a summary given by Kolupaila.

Kolupaila, S. (1964). "Accuracy of Current Meter Measurements," Discussion, *J. Hydr. Engrg*., ASCE, 90(1), 352-355.

This is a good discussion addressing the importance of sampling times and spatial resolution in current-meter measurements. Reference is made to research on the issue conducted in several European countries during the last 100 years.

Fenton, J.D. (2002). "The application of numerical methods and mathematics to hydrography." *Proc. 11th Australasian Hydrographic Conference*, Sydney, Australia, July 3-6. **{Wahlin PDF}**

This article concentrates on the uncertainty introduced due to the assumed velocity profile (mean velocity in a vertical).

Herschy, R.W. (1978). "Accuracy." *Hydrometry: Principles and practices*. Ed. Herschy, R.W., John Wiley and Sons. **{Wahlin}**

This chapter presents methods for estimating the uncertainty of current-meter discharge measurements, weirs and flumes, and stage-discharge relations. This is very similar to the ISO stuff.

Herschy, R.W. (2002). "The uncertainty in a current-meter measurement." *Flow Measurement and Instrumentation*, 13, 281-284. **{Wahlin PDF}**

This is a short summary of the uncertainty stuff from Herschy's Hydrometry book.

International Organization for Standardization. (1985). *Liquid flow measurement in open channels – velocity-area methods – collection and processing of data for determination of errors in measurements.* ISO 1088, Geneva, Switzerland. **{Wahlin}**

ISO's take on estimating the uncertainty of a current-meter discharge measurement. Similar to the approach taken by Pelletier (1998) and Sauer and Meyer (1992).

Lintrup, M. (1989). "A new expression for the uncertainty of a current meter discharge measurement." *Nordic Hydrology*, 20, 191-200. **{Wahlin}**

The author presents a method for estimating the uncertainty of a current-meter discharge measurement. It is not nearly as useful as Sauer and Meyer's paper.

Pelletier, P.M. (1988). "Uncertainties in the single determination of river discharge: a literature review." *Can. J. of Civ. Engr.*, 15, 834-850. **{Wahlin and Gonzalez}**

This publication presents a summary of over 140 publications on determining the uncertainty of current-meter discharge measurements. It is set up similar to Sauer and Meyer's paper, but it is not as good. Still, it's much better than Lintrup's paper.

This paper is essentially a literature review summarizing the evaluation of uncertainty of river discharge measurements with mechanical current meters. In the references reviewed by Pelletier, uncertainty is estimated on basic RSS instead of more advanced techniques such as FOV. Moreover, the conclusions of the work reviewed by Pelletier are based on flow measurements collected in rather "well behaved" measurement environments, so the uncertainty due to environmental effects on the total measurement uncertainty is only partially included.

Sauer, V.B., and Meyer, R.W. (1992). *Determination of error in individual discharge measurements*. USGS Open-File Report 92-144, Norcross, GA. **{Wahlin}**

The authors present a very good procedure for estimating the uncertainty of a current-meter discharge measurement.

Wahlin, B.T., Clemmens, A.J., and Replogle, J.A., (2001) Procedure for estimating measurement accuracy for surface water flows, Journal of Irrigation and Drainage Engineering. **{Wahlin}**

This paper presents a methodology for determining the accuracy of measured flow rates and computed water volumes for surface water flows measured with current meters, as is typical in rivers and large canals.

Whalley, N., Iredale, R.S., and Clare, A.F. (2001). "Reliability and uncertainty in flow measurement techniques – some current thinking." *Phys. Chem. Earth (C)*, 26(10-12), 743-749. **{Wahlin PDF}**

This is an article from the UK. It presents some qualitative, rather than quantitative, aspects of current-meter discharge measurements. It concentrates on calibration.

Stage-Discharge Relationships

Bailey, J.F., and Ray, H.A. (1966). "Definition of stage-discharge relation in natural channels by step-backwater analysis." USGS Water-Supply Paper 1869-A. **{Wahlin}**

This is a comparison of stage-discharge relations developed from current-meter discharge measurements and from step-backwater analysis. The agreement between the two methods is good (i.e., within ± 20%).

Dymond, J.R., and Christian, R. (1982). "Accuracy of discharge determined from a rating curve." *Hydrological Sciences Journal*, 27(4), 493-504. **{Wahlin}**

An error analysis shows that three types of errors influence the random error of a single discharge measurement determined from a rating curve. They are rating curve error, water level measurement error, and an error caused by ignoring all physical parameters, other than *water level, that affect discharge. Methods in the literature for evaluating the first two types of errors are reviewed and a method for evaluating the third type is given. The error of average discharge for an arbitrary period is also considered.*

Freeman, G.E., Copeland, R.R., and Cowan, M.A. (1995). "Quantifying stage discharge uncertainty at gaging stations." *Proc., 1st International Conference sponsored by Water Resources Engineering, ASCE*, San Antonio, TX, 14-18 August, 1779-1783. **{Wahlin}**

The authors analyzed the uncertainty associated with stage-discharge relations for more than 100 sites in the U.S.

Freeman, G.E., Copeland, R.R., and Cowan, M.A. (1996). "Uncertainty in stage-discharge relationships." *Proc., 7th IAHR International Symposium*, MacKay, Queensland, Australia, 29-31 July. **{Wahlin}**

The authors evaluated the uncertainty of 116 gage locations. The uncertainty was broken into three parts: 1) natural, 2) measurement, and 3) modeling. They also developed relationships to estimate the uncertainty of the stage-discharge relationship for ungaged streams and for the estimation of Manning's n values.

Herschy, R.W. (1994). "The analysis of uncertainties in the stage-discharge relation." *Flow Meas. Instrum.*, 5(3), 188-190. **{Wahlin}**

This is a very short paper that estimates the uncertainty of a stage-discharge relation. It essentially is a procedure outlining how to determine the uncertainty of a curve fit.

International Organization for Standardization. (1996). *Measurement of liquid flow in open channels – Part 1: Establishment and operation of a gauging station.* ISO 1100-1, Geneve, Switzerland. **{Wahlin}**

This standard does not talk about uncertainty, but it's related to Part 2, which does.

International Organization for Standardization. (1998). *Measurement of liquid flow in open channels – Part 2: Determination of the stage-discharge relation.* ISO 1100-2, Geneve, Switzerland. **{Wahlin}**

This standard has a brief section on estimating the uncertainty of the stage-discharge relation as well as the uncertainty of the daily mean discharge, the monthly mean discharge, and the annual mean discharge. This methodology is very similar to the one outlined by Herschy.

Schmidt, A.R. (2002). *Analysis of stage-discharge relations for open-channel flows and their associated uncertainties*. Ph.D. Dissertation, University of Illinois at Urbana-Champaign, Department of Civil and Environmental Engineering. **{Wahlin PDF}**

I'm waiting for Schmidt to send me his entire dissertation. Right now, I only have chapter 3, which has a section summarizing previous efforts to describe the uncertainty in stage-discharge relationships. His description is very thorough. I also have his bibliography which pointed out many other references we should try to obtain.

USACE. (1996). "Uncertainty of stage-discharge function." Chapter 5, *Risk-based analysis for flood damage reduction studies*. EM 1110-2-1619. **{Wahlin}**

The uncertainty was broken into three parts: 1) natural, 2) measurement, and 3) modeling. They also developed relationships to estimate the uncertainty of the stage-discharge relationship for ungaged streams and for the estimation of Manning's n values.

Venetis, C. (1970). "A note on the estimation of the parameters in logarithmic stage-discharge relationships with estimates of their error." *Bulletin of the International Association of Scientific Hydrology*, International Union of Geodesy and Geophysics, XV(2), 105-111. **{Wahlin}**

The author estimates the uncertainty of the parameters of a stage-discharge relationship using regression analysis.

Weirs and Flumes

Abt, S.R., Florentin, C.B., Genovez, A., and Ruth, B.C., 1995. Settlement and submergence adjustments for Parshall flume. Journal of Irrigation and Drainage Engineering, Vol. 121, No. 5. **{Wahl}**

A large set of experiments were conducted on small Parshall flumes (2-ft throat width or less) to develop a procedure for adjusting measurements to correct for effects of submergence and differential settlement which produces lateral and/or longitudinal slope of the flume. Several years ago Dr. Abt provided me with a computer program to perform the calculations. I have noted some inconsistencies in the data tables of this paper, and was told by Dr. Abt that a 1998 version of the paper corrects the problems, but I do not have a copy of it and do not know the exact reference.

Abt, S.R., and Ruth, B.C., 1997. Flume condition assessment in Colorado. Journal of the American Water Resources Association, Vol. 33, No. 1, February 1997. **{Wahl}**

Field installations of Parshall flumes were evaluated, and serious problems were found with more than half of the installations.

Clemmens, A., Wahl, T., Bos, M., and Replogle, J. (2001). *Water measurement with flumes and weirs*. International Institute for Land Reclamation and Improvement Publication 58, Wageningen, The Netherlands. **{Wahl}**

Authors give some basic uncertainty concepts related to flow measurement flumes.

Dodge, R.A., 1990. Effects of Mountain Stream Topography on the Accuracy of Small Parshall Flumes, U.S. Dept. of the Interior, Bureau of Reclamation, Research Report R-90-03. **{Wahl}**

This laboratory study of 6- and 9-inch Parshall flumes investigated approach flow problems with installations in small mountain streams. The study developed upstream pool modifications to improve approach flow conditions and measurement accuracy. The focus of the study is on eliminating bias errors and the flow conditions that contribute to excessive random uncertainty.

Jones, R.W. (2002). "A method for comparing the performance of open channel velocity-area flow meters and critical depth flow meters." *Flow Measurement and Instrumentation*, 13, 285-289. **{Wahlin PDF}**

Jones assumes that the uncertainty of critical depth flow meters (e.g., weirs and flumes) is well defined, and he uses them as a bench mark to compare the performance of velocity-area flow meters. This work only applies to rectangular channels.

Peck, H., 1988. Submerged flow in Parshall flumes. Model-Prototype Correlation of Hydraulic Structures, International Symposium, Colorado Springs, CO Aug. 9-11, 1988. **{Wahl}**

This laboratory study of 1-ft Parshall flumes revealed a discontinuity in the discharge-head relationship originally developed by Parshall. Parshall's original data was too sparse to reveal

the problem. For a range of submergences, two different discharges are possible. Errors as large as 12 percent can occur between actual discharge and that calculated from Parshall's rating equation. Improved submergence corrections were developed, and a submergence limit of 86 percent was recommended to avoid the zone of discontinuity.

Thomas, C.W. (1959). "Errors in measurement of irrigation water." *ASCE Transactions*, 124, 319-340. **{Wahlin}**

This is a very old work that attempts to identify sources of error in Parshall flumes and weirs. It points out many possible sources of error (e.g., sloping weir crest, ignoring the velocity of approach, rounding of the crest of the weir, etc.) and gives a quantitative approximation of the error for each identified source.

Annual Discharge

Anning, D.W. (2002). "Uncertainty in annual streamflow and change in reservoir content data from selected surface-water gaging stations on the Lower Colorado River streamflow-gaging station network 1995-99." USGS Fact Sheet 108-01, Tucson, AZ. **{Wahlin PDF}**

Qualitative outline of procedure used to estimate the standard error of annual discharges at various sites along the Lower Colorado River.

Anning, D.W. (2002). "Standard errors of annual discharge and change in reservoir content data from selected stations in the Lower Colorado River streamflow-gaging station network, 1995-99." USGS Water-Resources Investigation 01-4240, Tucson, AZ. **{Wahlin}**

Updated version of Moss and Gilroy's method. Applied to selected sites on the Lower Colorado River.

Burkham, D.E., and Dawdy, D.R. (1970). Error analysis of streamflow data for an alluvial *stream.* USGS Professional Paper 655-C. **{Wahlin}**

The authors computed the uncertainty of a computed discharge at a site by randomly choosing a group of discharge measurements for use in a rating analysis and using the remaining elements as a control group. The variance of the computed discharge was obtained by subtracting the variance of between the measured and true discharge from the variance between the measured and computed discharge. I don't like this approach very much.

Clarke, R.T. (1999). "Uncertainty in the estimation of mean annual flood due to rating-curve indefinition." *J. of Hydrology*, 222, 185-190. **{Wahlin PDF}**

The author assumes the stage-discharge relation can be described as $Q = \gamma(h + \alpha)^{\beta}$. *He takes into account the uncertainty in the parameter* α. *The annual maximum discharges are all estimated from the same stage-discharge relations, so they are correlated. This correlation is not usually accounted for. Clarke presents a method to estimate the uncertainty of the mean annual flood flow that takes into account this correlation as well as the uncertainties in the stage-discharge relationship.*

Clarke, R.T., Mendiondo, E.M., and Brusa, L.C. (2000). "Uncertainties in mean discharge from two large South American rivers due to rating curve variability." *Hydrological Sciences*, 45(2), 221-236. **{Wahlin}**

The authors assume that the sequence of mean annual discharges is a stationary time series with uncertainty expressed by the standard deviation of annual discharge. They use the uncertainty of the curve-fit stage-discharge relationship and the correlation between estimated mean annual discharges to obtain the uncertainty of the mean annual discharge.

Fontaine, R.A. (1983). Uncertainties in records of annual mean discharge in Maine. USGS Water-Resources Investigations 83-4025, Augusta, ME. **{Wahlin}**

Moss and Gilroy's uncertainty analysis applied to rivers in Maine.

Fontaine, R.A., Moss, M.E., Smath, J.A., and Thomas, W.O. (1984). Cost effectiveness of the *stream-gaging program in Maine – a prototype for nationwide implementation.* USGS Water-Supply Paper 2244. **{Wahlin}**

A more detailed account of Fontaine's earlier publication.

Gilroy, E.J., and Moss, M.E. (1981). Cost-effective streamgaging strategies for the Lower *Colorado River Basin.* USGS Open-File Report 81-1019. **{Wahlin}**

Application of Moss and Gilroy's uncertainty analysis to the Lower Colorado River Basin.

Matsuoka, I., Lee, R., and Thomas, W.O. (1985). Cost-effectiveness of the stream-gaging program in the Hawaii District. USGS Water-Resources Investigation Report 84-4126, Honolulu, HI. **{Wahlin}**

Moss and Gilroy's uncertainty analysis applied to rivers in Hawaii.

Meyer, R.W. (1998). Assessment of peak discharge uncertainty in the American River Basin, *California.* USGS Open-File Report 97-668, Sacramento, CA. **{Wahlin}**

Meyer uses flood-discharge data, current-meter discharge measurements, indirect measurements, and stage-discharge relations to estimate the uncertainty of annual peak floods.

Moss, M.E., and Gilroy, E.J. (1980). Cost effective stream-gaging strategies for the Lower Colorado River Basin: The Blythe field office operations. USGS Open-File Report 80-1048, Reston, VA. **{Wahlin}**

This is a very interesting paper. Moss and Gilroy assume that the uncertainty in the annual mean discharge at a stream gage is a function of the number of current-meter discharge measurements that are performed at that site. Using Kalman filtering techniques, the authors estimate the uncertainty in the annual mean discharge as a function of the number of current-meter discharge measurements that were performed. The mathematics in this paper are quite complex and some of the concepts are not explained very well. A couple of years ago, I talked to Moss and even he couldn't clear up some of my questions. As he was looking over his paper, he commented on how poorly he had written it. Moss and Gilroy wrote a computer program to perform the calculations outlined in this Open-File Report. Moss gave me a printed copy of the code (he wasn't sure if what he gave me was the complete code). This methodology has not been used very widely, but it is still very interesting.

Thomas, W.O., and Gilroy, E.J. (unpublished). Computer procedures for determining cost-effective stream-gaging strategies. Unpublished USGS Open-File Report. **{Wahlin}**

Description of the computer program used in Moss and Gilroy's uncertainty analysis.

Wahlin, B.T., Clemmens, A.J., and Replogle, J.A. (1997). Measurement accuracy for major *surface-water flows entering and leaving the Imperial Valley*. USDA, ARS, WCL Report 23, Phoenix, AZ. **{Wahlin}**

My attempt at estimating the uncertainty of the annual volume. Simpler than Moss and Gilroy's method but not as accurate. Considers both random and systematic uncertainties (Moss and Gilroy only consider random uncertainties). Heavily dependent on the user's ability to identify and quantify uncertainties. I am working on a new version of this paper that is easier to understand and follow.

Lower Colorado River Accounting System

Lane, W.L. (1998). "Statistical analysis of the 1995 lower Colorado River accounting system: an assessment of current procedures with recommended improvements." Prepared for the LCRAS Team and the USBR, contract number 1425-97-PG-30-07260. **{Wahlin}**

Statistical analysis of the LCRAS procedure. Uses standard statistical analysis techniques to estimate the uncertainty of various components of a mass-balance equation for the Colorado River. It has a good overview of uncertainty with a strong emphasis on systematic errors. Some of his uncertainty analysis is presented in a slightly different manner than what I have normally seen. It also discusses digitization and linearization errors, which aren't typically mentioned.

Lane, W.L. (2002). "Analysis, treatment and propagation of errors for crop evapotranspiration for the lower Colorado River accounting system." Prepared for the USBR, Boulder City, NV. **{Wahlin}**

An example of the uncertainty analysis described in Lane's 1998 report.

Closed-Conduit Flow Meters

Clark, W.J. (1965). *Flow measurement by square-edged orifice plate using corner tappings.* Pergamon Press, Oxford, UK. **{Wahlin}**

This book has a detailed section of how to properly install an orifice meter to minimize the error. It covers things like how to tap the pipe, how much straight approach length is needed, etc.

Hanson, B., and Schwankl, L., 1998. Error Analysis of Flowmeter Measurements. Journal of Irrigation and Drainage Engineering, Vol. 124, No. 5, Sept./Oct. 1998, pp. 248-256. **{Wahl}**

This paper examines the effect of flow disturbances on the performance of several varieties of closed-conduit flow meters, including propeller meters, pitot-tube devices, paddle wheel meters, and a Doppler acoustic meter. The effect of straightening vanes was also investigated.

Husain, Z.D., 1995. Theoretical Uncertainty of Orifice Flow Measurement. 7 pp. **{Wahl PDF}**

http://www.daniel.com/products/gas/orifice/senior/AppNotes/Theoretical Uncertainty of Orifice Flow Measurement172KB.pdf

Discusses the factors that can cause measurement errors and influence uncertainty. This report appears to be from a commercial flow meter company or maybe a consulting firm specializing in orifice meter applications..

International Organization for Standardization. (1991). *Measurement of fluid flow by means of pressure differential devices – Part 1: Orifice plates, nozzles and Venturi tubes inserted in circular cross-section conduits running full.* ISO 5167-1, Geneva, Switzerland. **{Wahlin}**

There is a small section on uncertainty in this standard.

Reader-Harris, M.J., Brunton, W.C., Gibson, J.J., Hodges, D., and Nicholson, I.G. (2001). "Discharge coefficients of Venturi tubes with standard and non-standard convergent angles." *Flow Measurement and Instrumentation*, 12, 135-145. **{Wahlin PDF}**

This paper presents some equations for the discharge coefficients of Venturi meters operating with water and high-pressure gas. It also gives estimates of the uncertainty of the discharge coefficients. There is a section on the error introduced from the pressure tap.

Replogle, J.A., 2002. Correcting Unreliable Velocity Distributions in Short Culverts and Canal Reaches. USCID/EWRI Conference on Energy, Climate, Environment and Water. San Luis Obispo, California, July 10-13, 2002. **{Wahl}**

This paper presents results of laboratory testing to evaluate the effect of distorted velocity distributions on the accuracy of closed-conduit and open channel flow meters and flumes. The majority of the paper talks about closed-conduit devices. The influence of straightening vanes and orifice-type flow conditioners is evaluated. Research on this topic is ongoing.

Ultrasonic Flow Meters

Johnson, A.L., Benham, B.L., Eisenhauer, D.E., and Hotchkiss, R.H., (2001). Ultrasonic Water Measurement in Irrigation Pipelines with Disturbed Flow. Transactions of the ASAE, Vol. 44 No. 4, pp. 899-910. **{Wahl}**

This paper investigates accuracy of USFM's at various distances downstream from flow disturbances commonly encountered in irrigation systems. Error correction multipliers were developed to overcome bias errors when flow meters were installed close to flow disturbing devices.

Acoustic Doppler Current Profilers

Nystrom, E.A., Oberg, K.A., and Rehmann, C.R. (2002). "Measurement of turbulence with acoustic Doppler current profilers – sources of error and laboratory results." ASCE conference on *Hydraulic Measurements and Experimentation Methods*. Estes Park, CO, July 28 – August 1. **{Wahlin PDF}**

The authors identify several sources of error in turbulence measurements made with ADCPs including: inaccuracy of Doppler-shift measurements, poor temporal and spatial measurement resolution, and inaccuracy of multi-dimensional velocities resolved from one-dimensional velocities measured at separate locations.

Simpson, M.R. (2001). Discharge measurements using a broad-band acoustic Doppler current profiler. USGS Open-File Report 01-1, Sacramento, CA. **{Wahlin PDF and Gonzalez}**

This Open-File Report has a section which describes the possible sources of error in an acoustic Doppler discharge measurement. This report is an update of Simpson and Oltman's 1992 paper that discuses important issues regarding the operating principles of broad-band ADCP's manufactured by RD Instruments.

Simpson, M.R., and Oltman, R.N. (1992). Discharge-Measurement System Using an Acoustic Doppler Current Profiler with Applications to Large Rivers and Estuaries. Open-File Report 91-487, U.S. Geological Survey. **{Gonzalez}**

This report includes an approximate procedure for computing uncertainty of Acoustic Doppler Current Profiler (ADCP's) for measuring discharge. Uncertainty is estimated using the RSS, and a series of assumptions are made that need to be revised for applying the approach to other sites.

Laser Doppler Velocimetry

Martin, P.B., Pugliese, G.J., and Leishman, J.G. (2000). "Laser Doppler velocimetry uncertainty analysis for rotor blade tip vortex measurements." American Institute of Aeronautics and Astronautics. **{Wahlin PDF}**

This paper presents a detailed uncertainty analysis of the beam alignment and vortex measurement technique used in LDV measurements. Sources of uncertainty are identified with optics calibration, data acquisition, and data reduction.

Environmental Measurements

Yoe, C.E. (1996). *An introduction to risk and uncertainty in the evaluation of environmental investments.* Institute for Water Resources Report 96-R-8. **{Wahlin PDF}**

This is a qualitative report designed to introduce people to the concepts of risk and uncertainty. It has a pretty good description of the difference between risk and uncertainty.

Yoe, C.E. (1996). *Incorporating risk and uncertainty into environmental evaluation: an annotated bibliography.* Institute for Water Resources Report 96-R-9. **{Wahlin PDF}**

A very detailed annotated bibliography on risk and uncertainty analysis. I need to take a closer look at this.

Sediment Measurements

McBean, E.A., and Al-Nassri, S. (1988). "Uncertainty in suspended sediment transport curves." *Journal of Hydraulic Engineering*, ASCE, 114(1), 63-74. **{Wahlin}**

The uncertainties implicit in suspended sediment transport curves are examined and the practice of using sediment load versus discharge is shown to be misleading, since the goodness of fit implied by this relation is spurious.

Shin, H.S., and Salas, J.D. (1996) "Uncertainty analysis of reservoir sedimentation." *Proc. ASCE North American Water and Environment Congress*, Anaheim, CA. **{Wahlin PDF}**

In estimating reservoir sedimentation, a number of uncertainties arise. These are related to annual streamflow, sediment load, sediment particle size, trap efficiency, and reservoir *operation. Monte Carlo simulation is used to quantify the uncertainty of reservoir sedimentation.*

Pressure Measurements

McKeon, B.J., and Smits, A.J. (2002). "Static pressure correction in high Reynolds number fully developed turbulent pipe flow." *Measurement Science and Technology*, 13, 1608-1614. **{Wahlin PDF}**

This is a new report on the error introduced in pressure measurements from the pressure tap. This study indicates that the correction term for the pressure tap continues to increase as the hole Reynolds number increases, which is contrary to previous studies.

Shaw, R. (1960). "The influence of hole dimensions on static pressure measurements." *J. of Fluid Mechanics*, 7, 550-564. **{Wahlin}**

This paper determines the error in a pressure measurement due to the size and shape of the pressure tap.

Numerical Computations and Modeling

Freitas, C.J., Ghia, U., Celik, I., Roache, P., and Raad, P. (2003). "ASME's quest to quantify numerical uncertainty." 41st AIAA Aerospace Sciences Meeting and Exhibit, Reno, NV, January 6-9. AIAA Paper 2003-627. **{Wahlin PDF}**

This paper reviews the formulation of methods for quantifying numerical uncertainty in simulations. The authors present a five-step approach for the estimation of numerical uncertainty based on Richardson Extrapolation and the Grid Convergence Index (whatever those are).

Oberkampf, W.L, DeLand, S.M, Rutherford, B.M., Diegert, K.V., and Alvin, K.F. (1999). "A new methodology for the estimation of total uncertainty in computational simulation." 40th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference and Exhibit, St. Louis, MO, April 12-15, 3061-3083, AIAA Paper 99-1612. **{Wahlin PDF}**

This paper develops a general methodology for estimating the total uncertainty in computational simulations that deal with the numerical solution of a system of partial differential equations. This methodology has six phases: 1) conceptual modeling of the physical system, 2) mathematical modeling of the conceptual model, 3) discretization of the model, 4) computer programming of the model, 5) numerical solution of the computer model, and 6) representation of the numerical solution.

Thompson, D.B., and Rogers, T.D. (1993). "Water surface profile computations – how many sections do I need?" *Proc., ASCE Conference on Hydraulic Engineering*, San Francisco, CA, July 25-30, 791-796. **{Wahlin PDF}**

This is a short article that has two simple examples that illustrate the importance of using enough computational cross-sections in hydraulic simulations. In some instances, using too few computational cross-sections led to errors as large at 2 feet.

USACE. (1986). *Accuracy of computed water surface profiles*. Hydrologic Engineering Center, RD 26, Davis, CA. **{Wahlin}**

This document describes the results of an investigation of the effects of using survey and mapping technology for determining cross-sectional coordinate geometry and the reliability of Manning's roughness coefficient on the accuracy of computed water surface profiles.

USACE. (1987). *Accuracy of computed water surface profiles: commercial survey guidelines for water surface profiles.* Hydrologic Engineering Center, RD 26A, Davis, CA. **{Wahlin}**

This document presents information that can be used to select the appropriate method of data collection for the development of water surface profiles.

Wesolowski, E.A. (1996). *Uncertainty analysis of the simulations of effects of discharging treated wastewater to the Red River of the North at Fargo, North Dakota, and Moorhead, Minnesota.* USGS Water-Resources Investigations Report 96-4015, Bismarck, ND. **{Wahlin}**

Wow! Now that's a title. In a previous work, the effects of discharging treated wastewater into two different rivers were simulated. In this work, Wesolowski performs a first order uncertainty analysis of the simulated constituent concentrations and property values using the Enhanced Stream Water Quality Model-Uncertainty Analysis, whatever that is.